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# (54) Title: MULTIPASS ARRANGEMENT AND DEVICE FOR SPECTRALLY BROADENING A LASER RADIATION

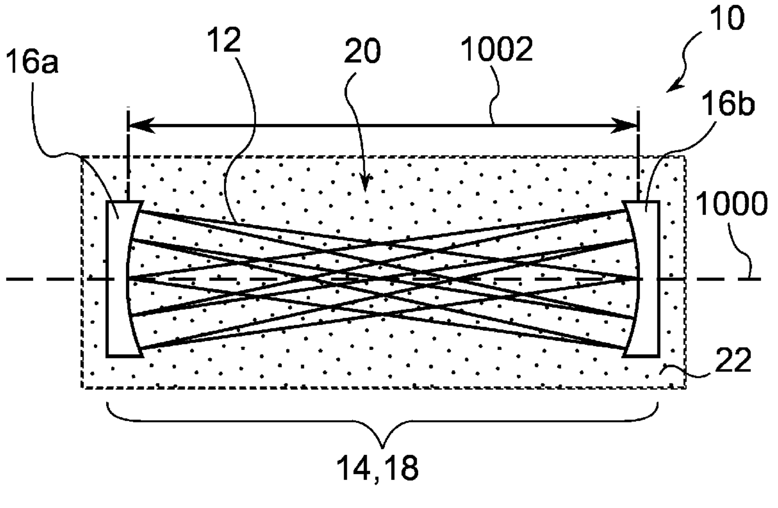

Fig. 1

(57) **Abstract:** Provided is a multipass arrangement (14) having a first mirror (16a) and a second mirror (16b) arranged on a central axis (1000) of the multipass arrangement (14), wherein the multipass arrangement (14) is adapted such that a laser radiation (12) coupled into the multipass arrangement (14) carries out multiple roundtrips between the first mirror (16a) and the second mirror (16b), characterized in that the first mirror (16a) and the second mirror (16b) are concave mirrors and that a distance (1002) of the first mirror (16a) from the second mirror (16b) along the central axis (1000) of the multipass arrangement (14) is 300 mm or less.

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# MULTIPASS ARRANGEMENT AND DEVICE FOR SPECTRALLY BROADENING A LASER RADIATION

The invention relates to a multipass arrangement, a device for spectrally broadening laser radiation, a device for temporally compressing a laser pulse, a use of a multipass arrangement for spectrally broadening a laser radiation, a light source, a time-resolved spectrometer, a pump-probe measurement system, an optical parametric amplifier system, a use of a light source for generating extreme ultraviolet radiation, a use of a light source for generating a super-continuum optical radiation, a use of a light source for providing femtosecond laser pulses for material processing, a use of a light source as a light source for multi-photon spectroscopy and/or coherent anti-Stokes Raman scattering spectroscopy, and a use of a light source as a light source for multi-photon lithography and/or polymerization applications. The invention is, thus, related to photonics, laser technology and applications of coherent light.

Multipass arrangements are conventionally used for providing multiple roundtrips of laser radiation coupled into the multipass arrangement and through possible interaction media arranged within the multipass arrangement. In photonic applications, multipass cells can be used for spatially homogenizing self-phase modulation of laser radiation in a nonlinear optical medium and distributing its accumulation over the propagation distance trough the nonlinear optical medium accumulated in multiple round trips. Multipass arrangement are, thus, commonly used for spectral broadening and temporal compression of laser pulses down to ultrashort femtosecond durations (see for instance: J. Weitenberg et al., IEEE J. Quantum Electron. 53, 1–4 (2017); M. Kaumanns, et al., Multipass spectral broadening with tens of millijoule pulse energy (Optical Society of America, 2019); K. Fritsch et al., Optics letters 43, 4643–4646 (2018); J. Schulte et al., Optics letters 41, 4511–4514 (2016); L. Lavenu et al., Optics express 27, 1958–1967 (2019)).

The underlying principle of multipass arrangements involves folding the path of the laser radiation propagation in order to go through a nonlinear media multiple times. In this way, the optical path length in the nonlinear medium can be increased while keeping the multipass arrangement at a moderate length.

Multipass arrangements for temporal compression of laser pulses have been used in commercial lasers, e.g. in Master Oscillator Power Amplifier (MOPA)-type systems that are capable of delivering variable pulse peak powers and energies, spanning multiple orders of magnitude (4 MW – 40 GW) or the micro-Joule to milli-Joule pulse energy range. For moderate pulse energies, i.e. for micro-Joule pulse energies, a bulk nonlinear optical medium is commonly used and for high pulse energies, such as milli-Joule pulse energies, coming along with high peak powers a gaseous nonlinear optical medium is commonly used.

However, existing methods for nonlinear pulse compression in multipass arrangements have various limitations. For efficient spectral broadening, dispersion management is of high relevance, especially if pulse durations in the femtosecond range shall be reached by the pulse compression. The commonly employed broadening setups, thus, use mirrors having tailored chirped mirror coatings for dispersion compensation in order to compensate optical dispersion occurring when the laser pulses propagate through the nonlinear optical media. However, as chirped mirror coatings typically suffer from a low Laser Induced Damage Threshold (LIDT), the used multipass arrangement require a large beam radius on the mirrors to limit the intensity and avoid a laser induced damage and/or nonlinear optical losses (see . O. Razskazovskaya et al., Optica, OPTICA 2, 803–811 (2015); L. Gallais et al., Journal of Applied Physics 117, 223103 (2015)). Consequently, the multipass arrangements conventionally used for pulse compression use mirrors having radius of curvature (ROC) well beyond 300mm and distances between the cell mirrors larger than 500 mm in order to increase the beam waist and by that to reduce the intensity at the mirrors (see J. Weitenberg et al., IEEE J. Quantum Electron. 53, 1–4 (2017); K. Fritsch et al., Optics letters 43, 4643–4646 (2018); J. Weitenberg et al., Optics express 25, 20502–20510 (2017);

L. Lavenu et al., Optics letters 43, 2252–2255 (2018); M. Hanna et al., J. Opt. Soc. Am. B 34, 1340 (2017); L. Lavenu et al., Optics letters 43, 2252–2255 (2018); M. Ueffing et al., *"Direct amplification of femtosecond pulses"*, Ludwig-Maximilians-Universität München; M. Kaumanns et al., Optics letters 43, 5877–5880 (2018)). Moreover, chirped mirror coatings for dispersion compensation offering a high reflectivity are mainly available for certain wavelengths ranges in the near infrared spectral range (see O. Razskazovskaya et al., Optica, OPTICA 2, 803–811 (2015)). However, when irradiated by laser radiation in the visible and/or ultraviolet spectral range, the dispersive coatings typically show overall low transmission as well as high nonlinear losses. This is particularly critical for shorter wavelength regions, for example, in green (ca. 515 nm) and ultraviolet (ca. 260 nm) spectral range. Dispersion compensation coatings having low nonlinear losses in this range are difficult to develop. These are further limitations of multipass arrangements for the use in spectral broadening and pulse compression applications.

The document DE 10 2020 113 631 B3 describes a multipass arrangement having a convex mirror and a concave mirror and its use for spectral broadening of laser pulses.

The problem solved by the invention relates to facilitating spectral broadening and pulse compression.

This problem is solved by a multipass arrangement, a device for spectrally broadening laser radiation, a device for temporally compressing a laser pulse, a use of a multipass arrangement for spectrally broadening a laser radiation, a light source, a time-resolved spectrometer, a pump-probe measurement system, an optical parametric amplifier system, a use of a light source for generating extreme ultraviolet radiation, a use of a light source for generating a super-continuum optical radiation, a use of a light source for providing femtosecond laser pulses for material processing, a use of a light source as a light source for multi-photon spectroscopy and/or coherent anti-Stokes Raman scattering spectroscopy, and a use of a light source as a light source for multi-photon lithography and/or polymerization applications having the features of the respective independent claim. Optional embodiments are provided in the dependent claims and the description.

In one aspect, a multipass arrangement is provided having a first mirror and a second mirror arranged on a central axis of the multipass arrangement, wherein the multipass arrangement is adapted such that a laser radiation coupled into the multipass arrangement carries out multiple roundtrips between the first mirror and the second mirror. A distance of the first mirror from the second mirror along the central axis of the multipass arrangement is 300 mm or less.

In another aspect, a device for spectrally broadening a laser radiation is provided. The device comprises a multipass arrangement having a first mirror and a second mirror arranged on a central axis of the multipass arrangement, wherein the multipass arrangement is adapted such that the laser radiation carries out multiple roundtrips between the first mirror and the second mirror when coupled into the multipass arrangement, and wherein a distance of the first mirror from the second mirror along the central axis of the multipass arrangement is 300 mm or less. The device further comprises a nonlinear optical medium arranged at least partly within the multipass arrangement such that the laser radiation coupled into the multipass arrangement passes through the nonlinear optical medium in at least several of the multiple roundtrips.

In yet another aspect, a device for temporally compressing a laser pulse is provided. The device comprises a multipass arrangement having a first mirror and a second mirror arranged on a central axis of the multipass arrangement, wherein the multipass arrangement is adapted such that the laser pulse carries out multiple roundtrips between the first mirror and the second mirror when coupled into the multipass arrangement, and wherein a distance of the first mirror from the second mirror along the central axis of the multipass arrangement is 300 mm or less. The device further comprises a nonlinear optical medium arranged at least partly within the multipass arrangement such that the laser pulse passes through the nonlinear optical medium in at least several of the multiple roundtrips. Moreover, the device comprises a dispersion compensation element for at least partly compensating an optical dispersion experienced by the laser pulse within the multipass arrangement.

In yet another aspect, a laser system for providing pulsed laser radiation is provided, wherein the laser system comprises a device for spectrally broadening the laser pulses according to an aspect of the present disclosure.

In yet another aspect, a use of a multipass arrangement for spectrally broadening a laser radiation is provided, the multipass arrangement having a first mirror and a second mirror arranged on a central axis of the multipass arrangement, wherein the multipass arrangement is adapted such that the laser radiation carries out multiple roundtrips between the first mirror and the second mirror when coupled into the multipass arrangement, and wherein a distance of the first mirror from the second mirror along the central axis of the multipass arrangement is 300 mm or less.

In yet another aspect, a light source is provided, the light source comprising a laser system adapted to emit a laser pulse and a device for temporally compressing the laser pulse. The device for temporally compressing the laser pulse comprises a multipass arrangement having a first mirror and a second mirror arranged on a central axis of the multipass arrangement, wherein the multipass arrangement is adapted such that the laser pulse carries out multiple roundtrips between the first mirror and the second mirror when coupled into the multipass arrangement, and wherein a distance of the first mirror from the second mirror along the central axis of the multipass arrangement is 300 mm or less. The device further comprises a nonlinear optical medium arranged at least partly within the multipass arrangement such that the laser pulse passes through the nonlinear optical medium in at least several of the multiple roundtrips, and a dispersion compensation element for at least partly compensating an optical dispersion experienced by the laser pulse within the multipass arrangement. The laser system of the light source may be adapted to emit a laser pulse having a FWHM pulse duration between about 200 fs to 10 ps.

The term “laser radiation” is used in the present disclosure for any kind of optical electromagnetic radiation, which may be frequency convertible by a nonlinear optical process, and in particular for coherent electromagnetic radiation. The laser radiation may originate from a laser oscillator and may optionally be further amplified in a laser amplifier and/or in an optical parametric amplification stage. The same applies, mutatis mutandis, to the term “laser pulse” indicating a pulsed form of laser radiation. Likewise, a laser system may be a system capable of emitting laser radiation. This may include a laser oscillator and/or a laser amplifier. However, also other light source capable of emitting coherent optical radiation may be regarded as a laser system.

A multipass arrangement is an arrangement of optical elements which deflects a laser radiation coupled into the multipass arrangement in such a way that it propagates several times in the multipass arrangement before the laser radiation is coupled out of the multipass arrangement. The redirection of the laser radiation optionally takes place by reflections of the laser radiation, so that the laser radiation changes its propagation direction in the multipass arrangement. In contrast to arrangements which guide the laser radiation by means of optical fibers through total internal reflection, in the multipass arrangement propagation of the laser radiation may take place in free space without a mode of the laser radiation being restricted by an optical fiber at any point along the optical path of the laser beam or laser pulse. The central axis of the multipass arrangement may be a central axis of the mode volume of the multipass arrangement. The central axis may at least partly coincide with an optical axis of the first mirror and/or the second mirror. The central axis does not necessarily have to be a straight line, but may comprise one or more kinks, for instance when the multipass arrangement comprises one or more intermediate mirrors for reflecting the laser radiation on a propagation between the first mirror and the second mirror. The distance of the first mirror from the second mirror is a separation distance between the first and the second mirror measured along the central axis, in particular between the center point of the reflective surface of said mirrors. In other words, the distance between the first mirror and the second mirror may be given by the total length of the central axis of the multipass arrangement.

The roundtrips of the laser radiation in the multipass arrangements may each have very similar optical paths through the multipass arrangement. In particular, in every or most of the roundtrips the laser radiation may be deflected by the same optical elements of the multipass arrangement, in particular the first mirror and the second mirror. For instance, the first roundtrip may include an incoupling and/or the last roundtrip may include an outcoupling of the laser radiation into / out of the multipass arrangement. Thus, according to some embodiments the first and/or the last roundtrip may deviate from the other roundtrips with respect to the optical elements deflecting the laser radiation. In some embodiments, a roundtrip does not exactly revert the optical path of the laser radiation propagating in the multipass arrangement but after completing one entire roundtrip, the laser radiation may hit the respective optical element, i.e. the first mirror and/or the second mirror, at a position strongly deviating from the position at the beginning of the roundtrip. In particular, in contrast to a resonator, the laser radiation propagates in the multipass arrangement on an individual optical path in each roundtrip, wherein the individual optical paths may not overlap with each other.

The nonlinear optical medium is a medium being optically transparent for the laser radiation and having a nonlinear susceptibility. The nonlinear optical medium is suitable for self-phase modulation of laser radiation propagating through the nonlinear optical medium which may result in a spectral broadening of the laser radiation. The nonlinear optical medium may comprise or consist of a nonlinear optical element, in particular a solid nonlinear optical element.

A pass of the laser radiation through the nonlinear optical medium represents a propagation of the laser radiation through the nonlinear optical medium. In some embodiments, each roundtrip of the laser radiation in the multipass arrangement may include two passes through the nonlinear optical medium, for instance one pass in a first direction and one pass in a second direction being opposite to the first direction. In other embodiments, each roundtrip may include only one pass through the nonlinear optical medium. For instance, the optical path of the roundtrip may be configured such that the laser radiation passes through the nonlinear optical medium only in one direction but does not pass through the nonlinear optical medium in a second direction. In yet other embodiments, each roundtrip may include more than one passes, in particular two passes, through the nonlinear optical medium. According to yet other embodiments, some roundtrips may not include a pass through the nonlinear optical medium. For instance, the device may be arranged such that in some roundtrips, such as directly after coupling the laser radiation into the multipass arrangement and/or directly before coupling the laser radiation out of the multipass arrangement, no pass through the nonlinear optical medium is included.

Temporally compressing a laser pulse means that the laser radiation is provided as pulsed laser radiation and that a pulse duration of the laser pulse(s) is shortened by the laser pulse(s) experiencing suitable optical dispersion. In particular, the laser pulse may experience second order dispersion and/or third order dispersion and/or a higher order dispersion resulting in a decrease of the pulse duration. The optical dispersion may originate in a material dispersion of a dispersion compensation element ,such as a bulk medium, through which the laser pulse propagates, and/or one or more chirped mirrors offering a suitable optical dispersion for the spectral range of the laser pulse. Hence, the dispersion compensation element may for instance comprise one or more chirped mirrors and/or a transparent bulk medium or consist of such. The temporal compression of a laser pulse means that the temporal envelope of the laser pulse is brought closer to the temporal envelope of a Fourier-limited temporal envelope. In other words, temporally compressing a laser pulse may include at least partly equalizing a spectral phase distribution of the frequency spectrum of the laser pulse. Typically, the temporal compression of a laser pulse requires prior spectral broadening of the laser pulse.

A device for spectrally broadening may be an entirely passive device. The device for spectral broadening being a passive device being a passive device means that no amplification of laser radiation is provided by the device and in the device. In other words, the device for spectral broadening may not have an active medium providing stimulated emission and light amplification.

The above-presented aspects provide the advantage that a multipass arrangement can be realized with small spatial dimensions. In particular, due to the limited length of the multipass arrangement and a correspondingly limited propagation length of the laser radiation within the multipass arrangement the optical dispersion experienced by the laser radiation propagating trough the multipass arrangement is limited and may be much smaller than in conventional longer multipass arrangements. This may further allow refraining from providing one or more dispersion compensation elements, as a compensation of the optical dispersion experienced within the multipass arrangement may be negligible. In particular, this may allow refraining from providing the first mirror and/or the second mirror as a chirped mirror, since no compensation of the optical dispersion is necessarily to be carried out. Instead, the first mirror and/or the second mirror may be provided as highly-reflective mirrors for the wavelength of the laser radiation and, thus, the multipass arrangement may provide a higher transmission, i.e. lower optical losses, than conventional longer multipass arrangements having chirped mirrors for dispersion compensation. As already mentioned, this may be particularly advantageous for keeping optical losses in the multipass arrangement small, which would otherwise originate from a sub-optimal reflectivity of the mirrors. In addition, using highly-reflective mirrors may be advantageous for using the multipass arrangement and devices comprising such a multipass arrangement for laser radiation in spectral ranges, for which no suitable chirped mirrors may be available. In particular, this may allow using the multipass arrangement and devices comprising highly-reflective mirrors for spectrally broadening and optionally for subsequent temporally compressing laser pulses in the visible and/or ultraviolet spectral range, in particular for optical wavelengths of about 550 nm and shorter. Conventional multipass arrangements are typically not usable in such spectral ranges due to the need of using chirped mirrors, which are typically not available for such wavelength ranges. Providing suitable coatings for dispersion compensation in the visible and/or ultraviolet region having a flat phase in a suitable quality is technically demanding and expensive. Mirrors operating in a broadband wavelength range, which is necessary for femtosecond lasers, have significant oscillations in the phase curve, which hinders a proper temporal compression of the laser pulses. Moreover, chirped mirrors for the visible and ultraviolet would require paired coatings, which further increases the costs. Thus, the above-mentioned aspects are advantageous in overcoming these limitations. Moreover, the limited length of the multipass arrangement, i.e. the limited distance of the first mirror from the second mirror along the central axis of the multipass arrangement, allows limiting the propagation length of the laser radiation within the multipass arrangement. This may be particularly helpful when applying the multipass arrangement and/or a device including said multipass arrangement in a setup, in which a temporal delay of different laser pulses has to be controlled. For instance, time-resolved spectrometers and/or pump-probe measurement systems may benefit from a limited propagation length of the laser pulses within the multipass arrangement, since said propagation length may have to be compensated for a different part of the laser pulses split off prior to the multipass arrangement in order to achieve a zero-delay between the parts of the laser pulses at the target.

Furthermore, the limited length of the multipass arrangement may come along with the use of a curved first mirror and a curved second mirror having a short radius of curvature and, hence, a short focal length. The fist mirror and/or the second mirror may have a concave curvature. Optionally both, the first and the second mirror, are concave mirrors. For instance, the sum of both radii of curvature may be equal to or longer than the distance of the first mirror and the second mirror. Due to the short radii of curvature and the correspondingly short focal length a small focus size may be achieved within the multipass cell and in particular within a nonlinear optical medium arranged within the multipass arrangement. Consequently, suitable focal intensities for nonlinear optical interaction may be achieved even with laser radiation of moderate peak power, such pulsed laser radiation having a peak power of 0,5 GW or less, or continuous wave laser radiation. Thus, due to the above-presented aspects, spectral broadening and optional pulse compression may be made available for laser radiation and in particular pulsed laser radiation having a moderate peak power below the critical power of the used nonlinear optical medium and/or for peak powers of 0,5 GW or less.

Moreover, the limited distance between the first and the second mirror may allow limiting the required aperture of the first and the second mirror. For conventional long multipass arrangements, the beam radius on the mirrors of the conventional multipass arrangement is large, which limits the amount of reflections and therefore the number of round trips through the nonlinear optical material due to the large mode inside the conventional multipass arrangement. However, in a shorter multipass arrangement having a distance of 300 mm or less between the first and the second mirror, it is possible to significantly reduce the aperture of the first and the second mirror to accommodate the same amount of bounces per mirror as in larger conventional multipass arrangements, reducing even further the overall size and volume of the cell. For instance, the first and the second mirror may be provided with an aperture, i.e. a diameter in case of a circular shaped mirror, of about 25,4 mm (1 inch). The coupling of the input radiation can optionally be performed via an opening in the mirror

As the distance of the first and the second mirror from the focus between said mirrors is limited by the short radii of curvature, the transversal beam diameter of the laser radiation at the first and the second mirror may be limited and smaller than in conventional longer multipass arrangements. This may allow keeping the aperture and/or the diameter of the first and /or second mirror small, such as for instance 10 cm or less. This provides the further advantage that the total mode volume and/or the internal volume of the multipass arrangement can be kept small. The latter is advantageous, as the space required by the multipass arrangement when integrated in a light source and/or a laser system can be kept small which, thus, facilitates its integration. Moreover, when using a gaseous nonlinear optical medium, the limited internal volume of the multipass arrangement may allow keeping a gas cell including the multipass arrangement small and, thus, keeping the required amount of gas to be filled into the gas cell small. This may contribute to low operating costs low, in particular when expensive gases are to be used within the gas cell.

The aspects may further provide the advantage that a compact and optionally cost efficient device for spectral broadening and optionally for pulse compression can be provided. Such a compact device may in particular be capable of spectrally broadening and optionally temporally compressing laser pulses, which are provided with a pulse duration FWHM (full width at half maximum, assuming for instance a Gaussian pulse shape) between 300 fs and 10 ps and a peak power of 0,5 GW or less. By using such a device for temporal pulse compression to a pulse duration FWHM between 20 fs and 50 fs and a resulting increase of the pulse peak power by a factor of 3 to 20 can be achieved. This extends the possible use areas of conventional laser systems to other fields, which require peak powers exceeding the presently achievable peak power of such laser systems.

The first mirror and/or the second mirror optionally are curved mirror having a radius of curvature of 150 mm or less. The distance of the first mirror from the second mirror may be equal to or less to the sum of the radii of curvature of the first mirror and the second mirror. This allows realizing a a short multipass arrangement. In particular, the absolute value of the radius of curvature may be 150°mm or less. In other words, when the radius of curvature is provided as a negative value, it may be considered as fulfilling this specification only when the absolute value in disregard of its negative character of the radius of curvature is 150 mm or less.

The first mirror and/or the second mirror may optionally have an aperture of 50,8 mm (1 inch) or less, optionally 38,1 mm (1,5 inch), 25,4 mm (1 inch) or 12,7 mm (0,5 inch) or less. Due to the short distance between the first mirror and the second mirror the beam diameter of the laser radiation at the first mirror and the second mirror may be kept small and, thus, the total internal volume and/or the mode volume of the multipass arrangement may be kept small facilitating the integration of the multipass arrangement in a device and/or a light source and/or allowing to keep the volume of a possible gas cell small, in which the multipass arrangement may be arranged.

The first mirror and/or the second mirror may be a highly reflective mirror, wherein the reflectivity may be determined at the central wavelength of the laser radiation intended to be used with the multipass arrangement. A mirror may be considered as being highly reflective if the reflectivity is 99% or higher and the group delay dispersion (GDD) is essentially zero, i.e. between -20 $fs^2$ and +20 $fs^2$, in a broad spectral range for the intended use. For instance, Figure 8 shows a comparison of the reflectivity and GDD for a pair of dispersive mirrors (sections a) and b), respectively) and highly reflective mirrors (sections c) and d)), each optimized for the read and near infrared spectral region. As can be seen, the highly reflective mirrors provide a GDD of essentially zero in the spectral range from about 720 nm to about 870 nm, while the dispersive mirrors cause a GDD of about -150 $fs^2$ in the same spectral region. This results in a significant temporal broadening of laser pulses reflected off such dispersive mirrors as compared to highly reflective mirrors having no dispersion compensation. At least one of the highly reflective mirrors may have a highly reflective dielectric multilayer coating, which may be optimized for the central wavelength of the laser radiation. Alternatively or additionally at least one of the highly reflective mirrors may have a highly reflective metal coating, such as a silver coating and/or an aluminum coating and/or a gold coating. In addition, at least one of the highly reflective coatings may have a protective coating for protecting the highly reflective coating from mechanically induced damages and/or laser induced damages. In particular the first mirror and the second mirror may be optimized for the visible and/or ultraviolet spectral range. Thus, the highly reflective coating may be adapted to be highly reflective for wavelengths in the visible and/or ultraviolet spectral range. Highly-reflective mirrors may provide the advantage that they offer a higher damage-threshold and lower or even negligible linear and nonlinear losses in the visible and ultraviolet spectral range as compared to chirped mirrors. Hence, the multipass arrangement may be provided with a higher total transmission as compared to a multipass arrangement having chirped mirrors.

Alternatively or additionally at least one of the first mirror and the second mirror may be a dispersive mirror. The terms “dispersive mirror” and “chirped mirror” are used as synonyms throughout this disclosure. The dispersive mirror may be a multilayer mirror inducing an optical dispersion on laser radiation when reflected off said mirror. Although not necessary in all optional embodiments, providing the first mirror and/or the second mirror as dispersive mirrors may assist in further reducing optical dispersion of the laser radiation and, hence, temporally compressing pulsed laser radiation.

The multipass arrangement may be configured as a Herriott cell. This provides a compact and robust configuration for the multipass arrangement. The multipass arrangement may optionally be arranged such that a laser radiation coupled into the multipass arrangement carries out at least 10 roundtrips between the first mirror and the second mirror. Due to the large number of round trips a large number of passes of the laser radiation through a nonlinear optical medium arranged within the multipass arrangement can be achieved and, hence, a long effective interaction length of the laser radiation with the nonlinear optical medium can be achieved.

The multipass arrangement may be configured as an asymmetric multipass cell. An asymmetric multipass cell may be realized by providing a first mirror having a different radius of curvature than the second mirror. Consequently, the focus within the multipass cell may be off-centered, i.e. at a position being closer to one of the first mirror and the second mirror. This may allow providing this first mirror or the second mirror, which ever is closer to the focus, with a smaller aperture, i.e. a smaller diameter in case of a circular shaped mirror, than the respective other mirror. This may facilitate in-coupling and/or out-coupling of laser radiation into the multipass arrangement and out of the multipass arrangement, respectively.

The nonlinear optical medium may comprise a solid nonlinear optical medium. For instance, the nonlinear optical medium may comprise a bulk quartz element and/or a bulk fused silica element having a thickness of 10 mm or less. Moreover, the nonlinear optical medium may comprise one or more of the following materials: MgF2, CaF2, YAG, fused silica, Sapphire, Si, Ge. A solid nonlinear optical medium may provide the advantage that a high nonlinear optical susceptibility can be provided and, hence, a strong nonlinear interaction can be achieved albeit a limited interaction length.

Alternatively or additionally the nonlinear optical medium may comprise a gaseous nonlinear optical medium. A gaseous nonlinear optical medium may provide the advantage that a long interaction length with the laser radiation can be realized. Moreover, gaseous nonlinear optical media may offer a lower risk of laser induced damage than some solid nonlinear optical media. Further, a gaseous nonlinear optical medium may allow adjusting the nonlinear susceptibility and, hence, the nonlinear optical interaction with the laser radiation by varying the temperature and/or pressure of the gaseous nonlinear optical medium. The gaseous nonlinear optical medium may comprise one or more of the following gases: Helium, Neon, Argon, Xenon, Nitrogen, $N_2O$, and Krypton.

The device may further comprise a gas cell being suitable for confining the gaseous nonlinear optical medium optionally at a pressure being higher than an atmospheric pressure. This allow adjusting the pressure of the gas and by this to adjust the nonlinear optical properties of the gaseous nonlinear optical medium. The multipass arrangement may optionally be arranged within the gas cell. This may be strongly facilitated due to the multipass arrangement having small dimensions and in particular a small length as compared to conventional multipass arrangements used for spectral broadening. Having the multipass arrangement arranged within the gas cell may result in the whole inner volume of the multipass arrangement being filled with the gaseous nonlinear optical medium. Hence, the interaction length of the laser radiation propagating through the multipass arrangement can be maximized while keeping the spatial dimensions of the multipass arrangement small. Alternatively or additionally a gas cell is arranged within the multipass cell. This allows providing a defined interaction length of the laser radiation and the gaseous nonlinear optical medium being smaller than the distance between the first and the second mirror. Moreover, this may allow providing a small and compact gas cell which may be particularly beneficial for providing gases at a pressure well beyond the atmospheric pressure.

The gas cell may have an inner volume of 1 L or less. Alternatively or additionally the gas cell may be adapted to confine the gaseous nonlinear optical medium at a volume-pressure product of 25 L·bar or less. This restriction of the volume or volume-pressure-product of the gaseous nonlinear optical medium may contribute to a high safety of the gas cell and may enable the use of such gas cells in environments which may not be accessible for gas cells having a higher volume and/or a larger volume-pressure-product. In particular, a restricted volume and/or volume-pressure-product may facilitate and/or avoid possible regulatory requirements for the use of such gas cells, in particular in laboratory and/or industrial environments or during the transport of such a device. Some applications of ultrafast laser systems may require limited pulse energies of 100 µJ or less. As a consequence, the use of a solid-state gain medium or a gas atmosphere at a very high pressure, for instance a pressure in a range from 10 bar to 50 bar or even higher, may be needed for an efficient spectral broadening. However, high pressure in combination with large volumes is often considered dangerous to operate and the enclosures may require a respective safety certification. These risks and requirements may be reduced when the gas volume of the gas cell and the gaseous nonlinear optical medium, respectively, is limited to 1 L or less and/or the volume-pressure product (liter*bar) is limited to 25 or less. Moreover, some gases which are typically used as a nonlinear optical medium, such as Helium, Neon, Krypton and/or Xenon, are often expensive. Hence, by reducing the volume, it is possible to significantly decrease the costs arising from a gas filling.

The disclosure further includes the following items:

In another aspect, a time-resolved spectrometer and/or a pump-probe measurement setup comprising a light source according to an aspect of the disclosure is provided. Due to the pulse compression and/or spectral broadening, a wide spectral coverage and/or a short temporal resolution in the range of 20 fs to 200 fs can be provided. As the multipass arrangement has compact dimensions and a moderate propagation length, the required efforts for compensating the time delay exhibited during the propagation through the multipass arrangement is limited.

In yet another aspect, an optical parametric amplifier system comprising a pump light source having a light source according to an aspect of the disclosure is provided. Due to the pump light source comprising a device for spectral broadening and/or pulse compression according to an aspect of the invention, the pump light source may be provided at reduced costs as compared to conventional pump light sources.

In yet another aspect, a use of a light source according to an aspect of the disclosure for generating extreme ultraviolet radiation is provided. This may provide a cost efficient and/or compact light source of extreme ultraviolet radiation suitable for emitting light in the wavelength range from about 10 nm to about 120 nm.

In yet another aspect, a use of a light source according to an aspect of the disclosure for generating a super-continuum optical radiation is provided. This may provide a compact and cost efficient light source for coherent broadband white light.

In another aspect, a use of a light source according to an aspect of the disclosure for providing femtosecond laser pulses for material processing is provided. Conventional industrial laser systems typically operate with pulse durations in the range from 300 fs – 10 ps. A peak power boost of factor 3-20 is possible by using a light source according to an aspect of the present disclosure and in particular by spectral broadening and pulse compression using a device according to an aspect of the present disclosure.

In another aspect, a use of a light source according to an aspect of the disclosure as a light source for multi-photon spectroscopy and/or coherent anti-Stokes Raman scattering, CARS, spectroscopy is provided. Moreover, a use of a light source according to an aspect of the disclosure as a light source for multi-photon lithography and/or polymerization applications is provided.

It is understood by a person skilled in the art that the above-described features and the features in the following description and figures are not only disclosed in the explicitly disclosed embodiments and combinations, but that also other technically feasible combinations as well as the isolated features are comprised by the disclosure. In the following, several optional embodiments and specific examples are described with reference to the figures for illustrating the disclosure without limiting the disclosure to the described embodiments.

Further optional embodiments will be illustrated in the following with reference to the drawings.

Figure 1 schematically shows a device for spectrally broadening a laser radiation according to an optional embodiment.

Figures 2A to 2D illustrate various exemplary spot patterns indicating the positions at which the laser radiation beam hits the first mirror and/or the second mirror.

Figures 3A and 3B present graphs demonstrating performance of spectral broadening by a device according to an optional embodiment.

Figure 4 presents a device for spectrally broadening a laser radiation according to another embodiment.

Figures 5A and 5B show results of spectral broadening and temporal compression by a device according to an optional embodiment.

Figure 6 depicts a comparison of a multipass arrangement according to an optional embodiment with a convention Herriott cell.

Figure 7 schematically depicts a light source according to an optional embodiment.

Figure 8 shows exemplary graphs of the reflectivity and GDD of a pair of dispersive mirrors and a highly reflective mirror for comparison.

In the drawings the same reference signs are used for corresponding or similar features in different drawings.

Figure 1 schematically shows a device 10 for spectrally broadening a laser radiation 12 according to an optional embodiment. The laser radiation 12 may be a pulsed laser radiation. The device 10 comprises a multipass arrangement 14 having a first mirror 16a and a second mirror 16b arranged on a central axis 1000 of the multipass arrangement 14 forming a Herriott cell 18. The first mirror 16a and the second mirror 16b are formed as spherical concave mirrors having a radius of curvature (ROC) of 50 mm each. Both mirrors are arranged concentrically and perpendicular to the central axis 1000. The multipass arrangement 14 is adapted such that the laser radiation 12 carries out multiple roundtrips between the first mirror 16a and the second mirror 16b when coupled into the multipass arrangement 14. A distance 1002 of the first mirror 16a from the second mirror 16b along the central axis 1000 of the multipass arrangement is 300 mm or less.

In addition, the device 10 comprises a nonlinear optical medium 20 arranged at least partly within the multipass arrangement 14 such that the laser radiation 12 coupled into the multipass arrangement 14 passes through the nonlinear optical 20 medium in at least several of the multiple roundtrips. The nonlinear optical medium 20 is provided as a gaseous nonlinear optical medium filling the inner volume of the multipass arrangement 14. In order to contain the gaseous nonlinear optical medium 20 within the multipass arrangement 14, the multipass cell 14 is arranged within a gas cell 22.

In order to obtain short laser pulses after coupling the laser radiation 12 out of the multipass arrangement 14, the optical dispersion of the device 10 is to be considered. For this reason, the device 10 is configured to limit the dispersion, which the laser radiation 12 experiences when propagating through the multipass arrangement 14, to a low level. The total nonlinearity gained in the multipass arrangement is quantified by the B-integral per pass of the laser radiation 12 through the nonlinear optical medium 20 in the multipass arrangement. As according to the presented optional embodiment the gaseous nonlinear optical medium 20 spreads out over the entire inner volume of the multipass arrangement, one pass of the laser radiation 12 through the nonlinear optical medium 20 extends from the first mirror 16a to the second mirror 16b or vice versa. The B-integral per pass is defined by equation (1) further below for a gas cell filled with gas, where $P_{peak}$ and $P_{crit}$ are the peak power and the critical power of the pulsed laser radiation, and L and R indicate the distance 1002 between the first and the second mirror and their ROC, respectively. It is further shown that in the multipass arrangement according to the presented embodiment the B-integral per roundtrip ($B_{rt}$) does not depend on the ROC of the first and second mirror 16a, 16b but exclusively on the $M_{rt}$ and $N_{rt}$ parameters (see equation (2)), which are defined as the number of pattern roundtrips ($M_{rt}$) and the number of reflections per mirror ($N_{rt}$) in the multipass arrangement 14, as seen in Figures 2A to 2D.

Figures 2A to 2D depict various exemplary spot patterns, indicating the positions at which the laser radiation beam hits the first mirror 16a and/or the second mirror 16b. The different spot patterns vary in the number of pattern roundtrips $M_{rt}$ and the reflections per mirror $N_{rt}$. The various spot patterns allow varying the number of roundtrips, which the laser radiation propagates through the multipass arrangement 12. In the Figures 2A to 2D, the solid lines indicate spot patterns having $N_{rt} = 6$ and the dashed lines indicate spot patterns having $N_{rt} = 7$. The spot patterns presented in Figures 2A and 2D differ from each other in the number $M_{rt}$, wherein the spot patterns have $M_{rt} = 1$in Figure 2A, $M_{rt} = 2$ in Figure 2B, $M_{rt} = 3$ in Figure 2C and $M_{rt} = 4$ in Figure 2D.

Taking the dependence of $B_{rt}$ from $N_{rt}$ and $M_{rt}$ into account, it is understood that the total B-integral ($B_{tot}$) accumulated by the laser radiation 12 during a propagation through the entire multipass arrangement 12 in a gas-filled gas cell does not directly depend on the length L or on the number of roundtrips in the multipass arrangement, $N_{rt}$ (see equation 3). The longest stable configuration of the multipass arrangement 14 is achieved when 2R = L, i.e. when the distance 1002 between the first and the second mirror 16a, 16b is equal to the sum of the radii of curvature ROC of the first and second mirror 16a, 16b (see D. Herriott et al., “Off-Axis Paths in Spherical Mirror Interferometers,” Appl. Opt. 3, 523 (1964)). In this case the argument $\left(\sqrt{\frac{L}{2R-L}}\right)$ of the term $\tan^{-1}\left(\sqrt{\frac{L}{2R-L}}\right)$ goes to infinity resulting in the function approaching $\pi/2$. This means that, the maximal B-integral per pass does not depend on the type of the multi-pass arrangement 14. In other words, very small multipass arrangement 14 having, for example, a concave first mirror 16a and a concave second mirror 16b each having ROC = 50 mm and a very large conventional multipass cell having a first mirror and a second mirror each having ROC = 5.000 mm would have the same B-integral once they are operated close to the 2R = L configuration. Accordingly, also small multipass arrangements 14 having a distance 1002 between the first and the second mirror 16a, 16b of 300 mm or less allow achieving a high B-integral in the same manner as conventional longer multipass arrangements do.

$$B_{rt} = \pi \frac{P_{peak}}{P_{crit}} \tan^{-1}\left(\sqrt{\frac{L}{2R - L}}\right) \quad (1)$$

$$B_{rt} = \pi \frac{P_{peak}}{P_{crit}} \frac{M_{rt}}{N_{rt}} \quad (2)$$

$$B_{tot} = B_{rt} \times N_{rt} = \pi \frac{P_{peak}}{P_{crit}} M_{rt} \quad (3)$$

In both cases, i.e. for short and for long multipass arrangements, the dispersion is mainly dictated by the propagation length, $L_{prop}$, in the gaseous nonlinear optical media. Therefore, short multipass arrangements 14 are advantageous as compared to longer multipass arrangements, as they offer a shorter $L_{prop}$ and hence a lower accumulated dispersion, which in addition allows the use of small ROC mirrors as a further advantage.

Another limitation to be considered is the fluence and/or intensity of the laser radiation at the first and second mirrors' 16a, 16b reflective surface, which should not exceed their laser induced damage threshold (LIDT). In this respect, highly reflective (HR) mirrors may be advantageous due to their typically higher LIDT as compared to chirped mirrors.

For laser radiation 12 being pulsed laser radiation having a pulse energy of 20 µJ and a pulse duration FWHM of 250 fs, the device 10 shown in Figure 1 having two highly reflective mirrors as first and second mirror 16a, 16b with a ROC of 50 mm each is discussed in the following. The first and the second mirror 16a, 16b have a highly reflective dielectric coating optimized for a wavelength of 515 and an aperture, i.e. a diameter, of 25.4 mm. The first and the second mirror 16a, 16b are placed in a 30 cm long and 15 cm wide high pressure gas cell 20, which may sustain pressures up to 20 bar and which comprises two 5 mm thick fused silica windows for input and output coupling of the laser radiation 12 into and out of the multipass arrangement 14. The parameters for this device 1ß0 can be seen in Table 1.

**Table 1**

| **Curvatures of first and second mirror** | **NLO medium** | **L (distance 1002)** | **Coating of mirrors** | **Input energy** | **$P_{peak}$** | **$P_{crit}$** |
|---|---|---|---|---|---|---|
| both 50 mm concave | 20 bar ($Ar/N_2$) | 99 mm | HR | 20 µJ | 75 MW | 2.5 GW |

The distance 1002 between the first and the second mirror 16a, 16b is adjusted such that it allows a total of 34 focusing spots and passes of the laser radiation through the nonlinear optical medium 20 while propagating through the multipass arrangement 14. The configuration of the multipass arrangement 14 is chosen close to the edge of the stability range by separating the first mirror 16a from the second mirror 16b along the central axis at a distance 1002 of 99 mm, which corresponds to 2R being nearly equal to L. This maximizes the propagation length of the laser radiation 12 through the gaseous nonlinear optical medium and, hence, the spectral broadening effect. The multipass arrangement 14 has a Gaussian eigenmode for a laser radiation 12 input beam being spectrally centered at 515 nm which is characterized by a waist of $w_0$ = 27 µm at $1/e^2$ intensity at the focal position and a $w_{1,2}$ = 300 µm waist on the mirror surface of the first mirror 16a ($w_1$) and the second mirror 16b ($w_2$), respectively. The fluence of the pulsed laser radiation 12 on the surface of the first and second mirror 16a, 16b is kept below 0,01 J/cm$^2$, which is below the LIDT of the mirrors. Further decreasing of the length of the multipass arrangement would increase the fluence on the mirror surface and, thus, reduce the maximum input energy of the pulsed laser radiation in order not to exceed the LIDT of the mirrors. The mode matching as well as input and output coupling may be enabled using a telescope and a focusing mirror (not shown) guiding the laser radiation beam through a slit in the first mirror 16a and/or the second mirror 16b.

Two different gases were used as the gaseous nonlinear optical medium 20, namely Argon and Nitrogen, of which Argon is an atomic gas and Nitrogen is a molecular gas. The intensity of the laser radiation at the focusing position within the multipass arrangement is about 10 TW/cm$^2$, which does not overcome the ionization threshold for neither of the gases and, thus, avoids a respective loss of energy and a degradation of beam quality. Argon exhibits a nonlinearity of $n_2 = 1{,}08 \cdot 10^{-23} \frac{m^2}{W}$ at atmospheric pressure and a group velocity dispersion of $GVD = 0{,}034425 \frac{fs^2}{mm}$, while Nitrogen exhibits a higher nonlinearity of $n_2 = 3 \cdot 10^{-23} \frac{m^2}{W}$ and a similar group velocity dispersion of $GVD = 0{,}035438 \frac{fs^2}{mm}$ at a wavelength of 515 nm. Both Argon and Nitrogen induce nearly twice the dispersion per mm of propagation in the visible spectral range and nearly three times more in the ultraviolet spectral range (Nitrogen: $GVD = 0{,}092521 \frac{fs^2}{mm}$; Argon: $GVD = 0{,}085620 \frac{fs^2}{mm}$; at a wavelength of 260 nm) than in the infrared spectral range (for instance at a wavelength of 800 nm) when compared to infrared laser pulses. This dramatic increase of dispersion in the visible and ultraviolet spectral range as compared to the infrared spectral range makes it particularly advantageous to limit the total propagation length of the laser radiation through the multipass arrangement and particularly through the nonlinear optical medium $L_{prop}$ at a low level.

The performance of the device 10 in spectral broadening for Argon and Nitrogen, respectively, used as gaseous nonlinear optical medium is presented in graph 100 in Figures 3A and in graph 200 in Figure 3B. Both graphs 100, 200 show the normalized spectral intensity of the input laser radiation 102, 202, the simulated normalized output spectrum 104 and the measured normalized output spectrum 106. The vertical axis indicates the spectral intensity (in arbitrary units) and the vertical axis indicates the wavelength (in nm). The laser radiation 12 is pulsed laser radiation having an input pulse energy of 20 µJ and a pulse duration FWHM of 250 fs, with 3W average power. The maximum spectral broadening effect, when using Argon, was achieved for a pressure of the gaseous nonlinear optical medium of 20 bar. A further increase of the pressure of the gaseous nonlinear optical medium 20 leads to a reduction of transmission efficiency due to bandwidth limitations of the first and second mirror 16a and 16b, as the broadened spectrum exceeds the spectral bandwidth supported by the mirrors, and due to an undesired occurrence of ionization of the gaseous nonlinear optical medium 20. The self-phase modulated and broadened output spectrum 106 spans a spectral range from 490 nm to 540 nm, with a spectral width of 34 nm at FWHM. The broadened spectrum of the laser radiation 12 supports a Fourier limited pulse duration FWHM of 19 fs, as seen in the inlay 108 of Figure 3A. An overall transmission of the device 10 of 90 % was measured, with small to negligible variation depending on the used pressure of the gaseous nonlinear optical medium. A similar behavior was observed for Nitrogen being used as nonlinear optical medium, however with a lower pressure inside the gas chamber 22. These results, which are shown in Figure 3B, confirm the predicted expectations, due to its higher ratio between nonlinearity and dispersion as compared to Argon. Thus, using Nitrogen at a pressure of 6 bar, the input spectrum 202 of the laser radiation 12 can be spectrally broadened from initial 3 nm to about 38 nm (FWHM) of the measured output spectrum 206. The transmission through the device 10 remains at about 90%, as before with no significant beam quality degradation. The Fourier time limited supported by the achieved spectrum is 17 fs FWHM, as shown in the inlay 208 of Figure 3B.

A device 10 for spectrally broadening a laser radiation 12 according to another embodiment is discussed in the following with reference to Figure 4. The parameters of said device 10 are indicated in the following table 2:

**Table 2**

| **Curvatures of first and second mirror** | **NLO medium** | **L (distance 1002)** | **Coating of mirrors** | **Input energy** | **$P_{peak}$** | **$P_{crit}$** |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| 38 mm and 25 mm (both concave) | solid fused-silica plate (6,35 mm) | 62 mm | diserpsive | 500 nJ | 2 MW | 4 MW |

The device 10 according to this embodiment may be particularly suitable for spectrally broadening and optionally compressing laser pulses having a pulse energy of 1 µJ or less. To spectrally broaden and optionally compress laser pulses in this energy range, the multipass arrangement 14 offers hard focusing of the laser radiation 12 inside the nonlinear optional medium 20 to achieve significant spectral broadening. The nonlinear optical medium (NLO medium) is a thin plate of fused-silica having a thickness of 6,35 mm.

The multipass arrangement 14 is based on a Herriott cell configuration comprising a spherical concave first mirror 16a and a spherical concave second mirror 16b having a diameter of 25.4 mm (1 inch) offering a high focusing power. In particular, the first mirror 16a has a ROC of 38 mm and the second mirror 16b has a ROC of 25 mm and both mirrors 16a, 16b are placed at a distance 1002 along the central axis of L = 62 mm, as illustrated in Fig. 4. The concave surfaces of the concave first and second mirrors 16a, 16b are dispersively coated, i.e. the first mirror and the second mirror 16a, 16b are both chirped mirrors, to compensate a Group Delay Dispersion (GDD) of -120 $fs^2$ to account for the nonlinear optional medium 20 used inside the multipass arrangement 14.

The nonlinear optical medium 20 is formed of an anti-reflection coated fused-silica plate having a diameter of 25 mm and a thickness of 6,35 mm, which is placed in the focal plane of the multipass arrangement 14. Coupling into and out of the multipass arrangement 14 is achieved via a cut into one of the first mirror 16a and/or the second mirror 16b. The multipass arrangement 14 is configured to provide 19 bounces of the incoupled laser radiation 12 per each of the first mirror 16a and the second mirror 16b, i.e. 19 round trips. This yields 38 passes of the laser radiation 12 through the nonlinear optical medium in total. The beam diameter of the laser radiation 12 for a Gaussian beam with an eigen-q-parameter of the multipass arrangement is $w_1$ = 300 µm on the first mirror 16a and $w_2$ = 200 µm on the second mirror 16b. The focus in the multipass arrangement 14 has an estimated size of $w_0$ = 40 µm ($1/e^2$). A nonlinear phase per bounce off one of the chirped first mirror 16a and chirped second mirror 16b amounts to phi = 0,6 for an input energy per laser pulse of 500 nJ. The total achieved propagation distance within the nonlinear optical medium accumulated over the whole propagation of the laser radiation 12 through the multipass arrangement 14 amounts to about 24 cm.

The source of laser radiation 12 used for demonstrating the operability of the device 10 according to this embodiment is a commercially available high-power laser source (Light Conversion PHAROS) delivering pulsed laser radiation 12 with an average power of up to 15 W and a pulse duration (FWHM) of 250 fs at a repetition rate of 1 MHz. The laser pulses were attenuated, using a thin film polarizer and a wave plate to cover the range of pulse energy from a few nanojoules to about 2 µJ. A dispersion compensation element is provided as a chirped-mirror compressor comprising four chirped mirrors was used, of which each mirror provides $-400\ \mathrm{fs}^2$ GDD.

A comparison between the laser pulses spectrally broadened by the device 10 and compressed by the chirped-mirror compressor and its calculated Fourier transform limit is shown in the graphs in Figures 5A and 5B. Graph 200 in Figure 5A shows at the horizontal axis the wavelength in nanometers and the normalized intensity on the vertical axis. Spectrum 202 represents the input spectrum of the pulsed laser radiation coupled into the device 10 for spectral broadening having a pulse energy of 500 nJ. Spectrum 204 indicates the spectrally broadened output spectrum of the pulsed laser radiation 12 after spectrally broadening and temporal compression. Spectrum 206 represents a theoretical simulation of the spectrum to be expected after spectral broadening and temporal compression. As can be seen, the device 10 for spectral broadening offers a significant spectral broadening of the initial spectrum of the laser radiation 12, wherein the measured results are in good agreement with the simulated prediction. Graph 300 in Figure 5B depicts a comparison of the measured results and the simulated prediction of the spectrally broadened and temporally compressed laser pulses in time domain, wherein the horizontal axis shows the time in femtoseconds, the vertical axis shows the normalized intensity in arbitrary units. The solid line 302 represents the measured pulse shape of the spectrally broadened and compressed laser pulses and the dashed line 304 represents the calculated Fourier time limit. The pulse duration FWHM of the spectrally broadened and temporally compressed laser pulses amounts to about 50 fs, which is about five times shorter than the input laser pulses having a FWHM pulse duration of about 250 fs. In addition, graph 300 demonstrates that a compression of the laser pulses which were spectrally broadened in a device 10 and subsequently compressed in a chirped mirror compressor matches very closely the calculated Fourier time limit, which indicates good phase properties and a good compressibility of the laser pulses spectrally broadened in the device 10. The results have been achieved by one single propagation of the pulsed laser radiation 12 through the device 10, i.e. the laser radiation 12 was only once coupled into and out from the multipass arrangement 14.

Figure 6 schematically depicts a comparison of a multipass arrangement 14 according to an optional embodiment of the disclosure with a convention Herriott cell 30. As can be seen, the multipass arrangement 14 has a significantly shorter length defined by the distance 1002 of the first mirror 16a and the second mirror 16b, than the conventional Herriott cell 30. Moreover, the shown optional embodiment of the multipass arrangement 14 is configured as an asymmetric multipass arrangement 14, wherein the first mirror 16a and the second mirror 16b differ from each other in their ROC and the aperture. The multipass arrangement 14 offers inter alia the advantage over the conventional, longer Herriott cell 30 that the optical dispersion can be kept lower than in the conventional Herriott cell 30 and that the multipass arrangement can be provided with more compact spatial dimensions.

Figure 7 schematically depicts a light source 40 according to an optional embodiment comprising a device 10 for spectral broadening of a laser radiation. Furthermore, the light source comprises a laser system 42 emitting laser pulses, which may then be spectrally broadened and optionally temporally compressed by the device 10. According to an optional embodiment, the device 10 may be a part of the laser system 42.

Figure 8 depicts a comparison of an exemplary dispersive mirror and a highly-reflective mirror. Sections a) and c) show the reflectivity of a pair of dispersive mirrors (section a) and of a reflective mirror (section c) in % over the wavelength in nanometers. Sections b) and d) show the group delay dispersion (GDD) of the pair of dispersive mirrors and their average in $fs^2$ over the wavelength in nanometers at an angle of incidence of 0°. As can be seen in the comparison, the highly reflective mirror has a central wavelength region from about 720 nm to about 850 nm, in which the GDD is essentially zero, while the dispersive mirrors cause a significant GDD of about -150 $fs^2$ in the same spectral region. Thus, using highly reflective mirrors as first and second mirror of a multipass arrangement allow reducing possible phase distortions of laser pulses or laser radiation propagating through said multipass arrangement.

## List of reference signs

| | |
|---|---|
| 10 | device for spectrally broadening a laser radiation |
| 12 | laser radiation |
| 14 | multipass arrangement |
| 16a | first mirror |
| 16b | second mirror |
| 18 | Herriott cell |
| 20 | nonlinear optical medium |
| 22 | gas cell |
| 30 | conventional Herriott cell |
| 40 | light source |
| 42 | laser system |
| 100, 200 | graph |
| 102, 202 | input spectrum |
| 104, 204 | simulated output spectrum |
| 106, 206 | measured output spectrum |
| 108, 208 | inlay indicating the Fourier limited pulse shape |
| 200 | graph |
| 202 | measured input spectrum of laser radiation |
| 204 | measured output spectrum of laser radiation |
| 206 | simulated output spectrum of laser radiation |
| 300 | graph |
| 302 | measured laser pulse in time domain after spectral broadending and compression |
| 304 | simulated Fourier time limit of laser pulse after spectral broadending and compression |
| 1000 | central axis of multipass arrangement |
| 1002 | distance between first and second mirror |

## Claims

1. Multipass arrangement (14) having a first mirror (16a) and a second mirror (16b) arranged on a central axis (1000) of the multipass arrangement (14), wherein the multipass arrangement (14) is adapted such that a laser radiation (12) coupled into the multipass arrangement (14) carries out multiple roundtrips between the first mirror (16a) and the second mirror (16b), **characterized in that** the first mirror (16a) and the second mirror (16b) are concave mirrors and that a distance (1002) of the first mirror (16a) from the second mirror (16b) along the central axis (1000) of the multipass arrangement (14) is 300 mm or less.

2. Multipass arrangement (14) according to claim 1, wherein the first mirror (16a) and/or the second mirror (16b) is a curved mirror having a radius of curvature of 150 mm or less.

3. Multipass arrangement (14) according to claim 1 or 2, wherein the first mirror (16a) and/or the second mirror (16b) has an aperture of 50,8 mm or less and optionally of 25,4 mm or less.

4. Multipass arrangement (14) according to any one of the preceding claims, wherein the first mirror (16a) and/or the second mirror (16b) is a highly reflective mirror.

5. Multipass arrangement (14) according to claim 4, wherein at least one of the highly reflective mirrors has a highly reflective dielectric multilayer coating or a highly reflective metal coating.

6. Multipass arrangement (14) according to any one of the preceding claims, wherein at least one of the first mirror (16a) and the second mirror (16b) is a dispersive mirror.

7. Multipass arrangement (14) according to any one of the preceding claims, wherein the multipass arrangement (14) is configured as a Herriott cell.

8. Multipass arrangement (14) according to any one of the preceding claims, wherein the multipass arrangement (14) is arranged such that a laser radiation (12) coupled into the multipass arrangement (14) carries out at least 10 roundtrips between the first mirror (16a) and the second mirror (16b).

9. Multipass arrangement (14) according to any one of the preceding claims, wherein the first mirror (16a) and the second mirror (16b) are optimized for the visible and/or ultraviolet spectral range.

10. Multipass arrangement (14) according to any one of the preceding claims, wherein the multipass arrangement (14) is configured as an asymmetric multipass cell.

11. Device (10) for spectrally broadening a laser radiation (12), the device (10) comprising:

- a multipass arrangement (14) having a first mirror (16a) and a second mirror (16b) arranged on a central axis (1000) of the multipass arrangement (14), wherein the multipass arrangement (14) is adapted such that the laser radiation (12) carries out multiple roundtrips between the first mirror (16a) and the second mirror (16b) when coupled into the multipass arrangement (14), and wherein the first mirror (16a) and the second mirror (16b) are concave mirrors and a distance (1000) of the first mirror (16a) from the second mirror (16b) along the central axis (1000) of the multipass arrangement (14) is 300 mm or less;
- a nonlinear optical medium (20) arranged at least partly within the multipass arrangement (14) such that the laser radiation (12) coupled into the multipass arrangement (14) passes through the nonlinear optical medium (20) in at least several of the multiple roundtrips.

12. Device (10) according to claim 11, wherein the nonlinear optical medium (20) comprises a solid nonlinear optical medium.

13. Device (10) according claim 11 or 12, wherein the nonlinear optical medium (20) comprises a gaseous nonlinear optical medium.

14. Device (10) according to claim 13, further comprising a gas cell (22) being suitable for confining the gaseous nonlinear optical medium (20) optionally at a pressure being higher than an atmospheric pressure.

15. Device (10) according to claim 14, wherein the multipass arrangement (14) is arranged within the gas cell (22) or wherein the gas cell (22) is arranged within the multipass cell (14).

16. Device (10) according to claim 14 or 15, wherein the gas cell (22) has an inner volume of 1 L or less and/or wherein the gas cell (22) is adapted to confine the gaseous nonlinear optical medium (20) at a volume-pressure product of 25 L·bar or less.

17. Device (10) for temporally compressing a laser pulse, the device comprising:

- a multipass arrangement (14) having a first mirror (16a) and a second mirror (16b) arranged on a central axis (1000) of the multipass arrangement (14), wherein the multipass arrangement (14) is adapted such that the laser pulse carries out multiple roundtrips between the first mirror (16a) and the second mirror (16b) when coupled into the multipass arrangement (14), and wherein the first mirror (16a) and the second mirror (16b) are concave mirrors and a distance (1002) of the first mirror (16a) from the second mirror (16b) along the central axis (1000) of the multipass arrangement (14) is 300 mm or less;
- a nonlinear optical medium (20) arranged at least partly within the multipass arrangement (14) such that the laser pulse passes through the nonlinear optical medium (20) in at least several of the multiple roundtrips;

- a dispersion compensation element for at least partly compensating an optical dispersion experienced by the laser pulse within the multipass arrangement (14).

18. Laser system (42) for providing pulsed laser radiation, wherein the laser system comprises a device (10) for spectrally broadening the laser pulses according to any one of the claims 11 to 17.

19. Use of a multipass arrangement (14) for spectrally broadening a laser radiation (12), the multipass arrangement (14) having a first mirror (16a) and a second mirror (16b) arranged on a central axis (1000) of the multipass arrangement (14), wherein the multipass arrangement (14) is adapted such that the laser radiation (12) carries out multiple roundtrips between the first mirror (16a) and the second mirror (16b) when coupled into the multipass arrangement (14), and wherein the first mirror (16a) and the second mirror (16b) are concave mirrors and a distance (1002) of the first mirror (16a) from the second mirror (16b) along the central axis (1000) of the multipass arrangement (14) is 300 mm or less.

20. Use according to claim 17, wherein the multipass arrangement (14) is used for spectrally broadening laser radiation (12) which is spectrally centered in the visible and/or ultraviolet spectral range.

21. Light source (40) comprising:
    - a laser system (42) adapted to emit a laser pulse;
    - a device (10) for temporally compressing the laser pulse, the device comprising:
        + a multipass arrangement (14) having a first mirror (16a) and a second mirror (16b) arranged on a central axis (1000) of the multipass arrangement (14), wherein the multipass arrangement (14) is adapted such that the laser pulse carries out multiple roundtrips between the first mirror (16a) and the second mirror (16b) when coupled into the multipass arrangement (14), and wherein the first mirror (16a) and the

second mirror (16b) are concave mirrors and a distance (1002) of the first mirror (16a) from the second mirror (16b) along the central axis (1000) of the multipass arrangement (14) is 300 mm or less;

+ a nonlinear optical medium (20) arranged at least partly within the multipass arrangement (14) such that the laser pulse passes through the nonlinear optical medium (20) in at least several of the multiple roundtrips;
+ a dispersion compensation element for at least partly compensating an optical dispersion experienced by the laser pulse within the multipass arrangement (14).

22. Light source (40) according to claim 19, wherein the laser system (42) is adapted to emit a laser pulse which is spectrally centered in the visible or ultraviolet spectral range.

23. Light source (40) according to claim 19 or 20, wherein the laser system (42) is adapted to emit a laser pulse having a FWHM pulse duration between 300 fs to 10 ps.

24. Time-resolved spectrometer comprising a light source (40) according to any one of claims 19 to 21.

25. Pump-probe measurement system comprising a light source (40) according to any one of claims 19 to 21.

26. Optical parametric amplifier system comprising a pump light source having a light source (40) according to any one of claims 19 to 21.

27. Use of a light source (40) according to any one of claims 19 to 21 for generating extreme ultraviolet radiation.

28. Use of a light source (40) according to any one of claims 19 to 21 for generating a super-continuum optical radiation.

29. Use of a light source (40) according to any one of claims 19 to 21 for providing femtosecond laser pulses for material processing.

30. Use of a light source (40) according to any one of claims 19 to 21 as a light source for multi-photon spectroscopy and/or coherent anti-Stokes Raman scattering, CARS, spectroscopy.

31. Use of a light source (40) according to any one of claims 19 to 21 as a light source for multi-photon lithography and/or polymerization applications.

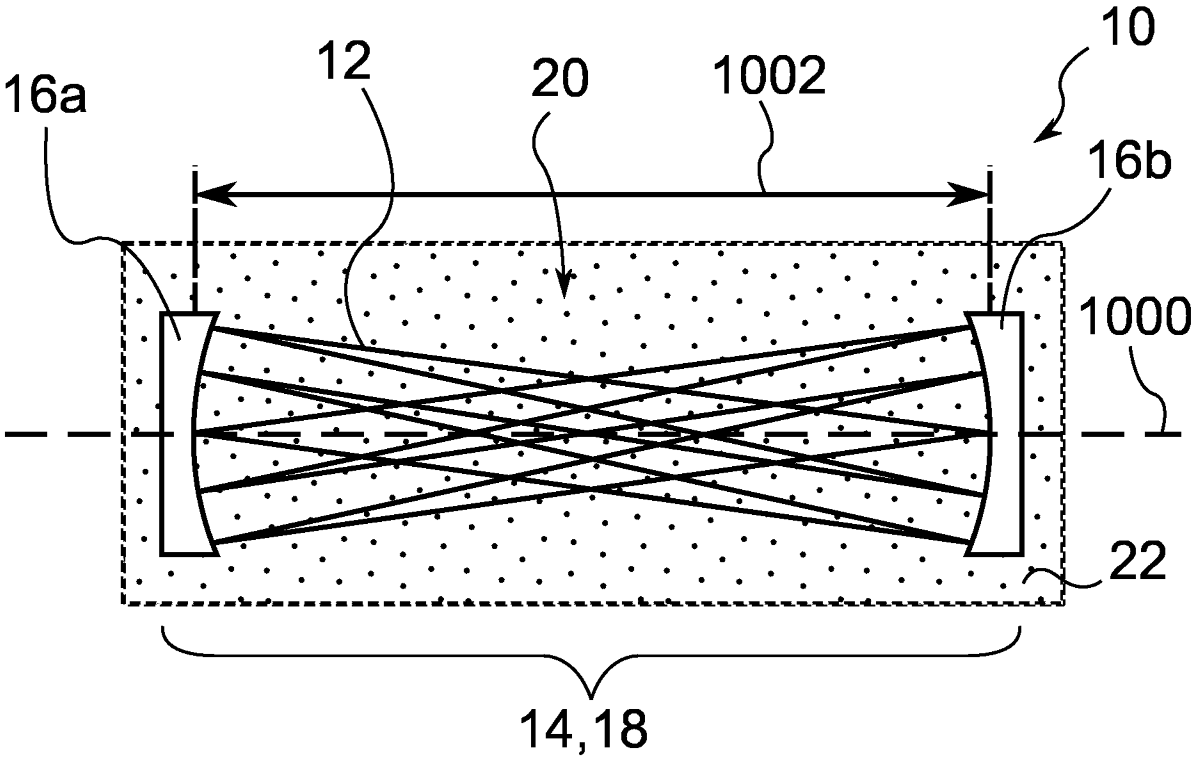


Fig. 1

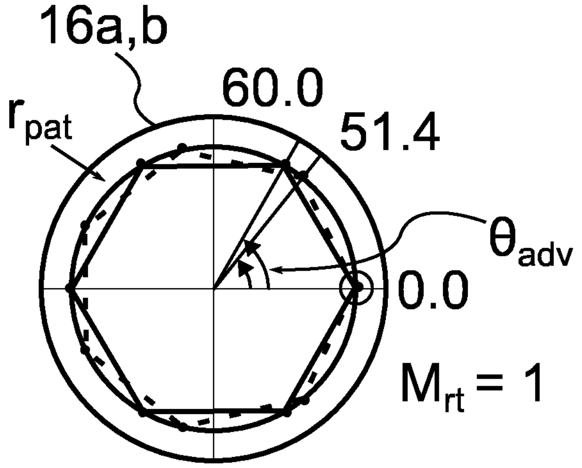


Fig. 2A

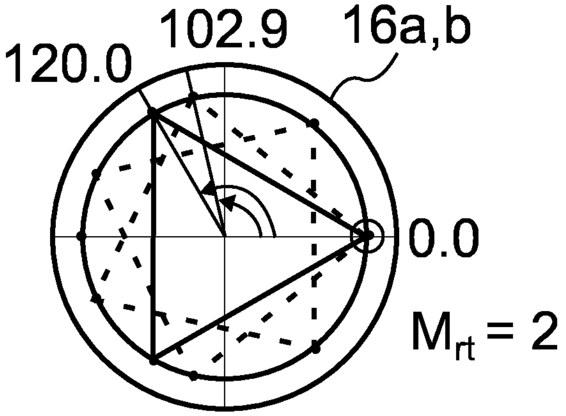


Fig. 2B

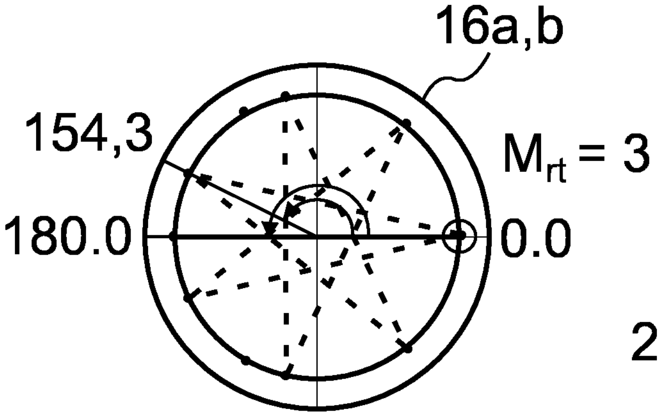


Fig. 2C

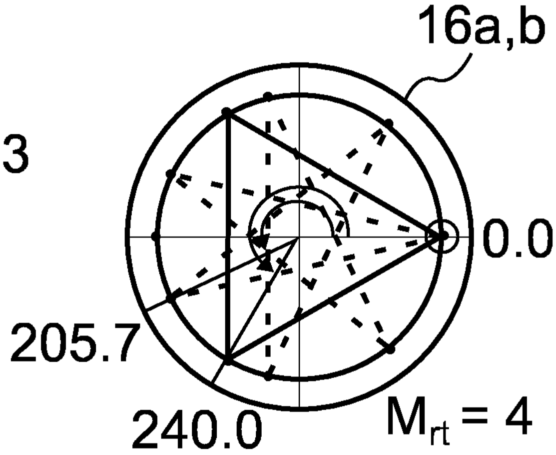


Fig. 2D

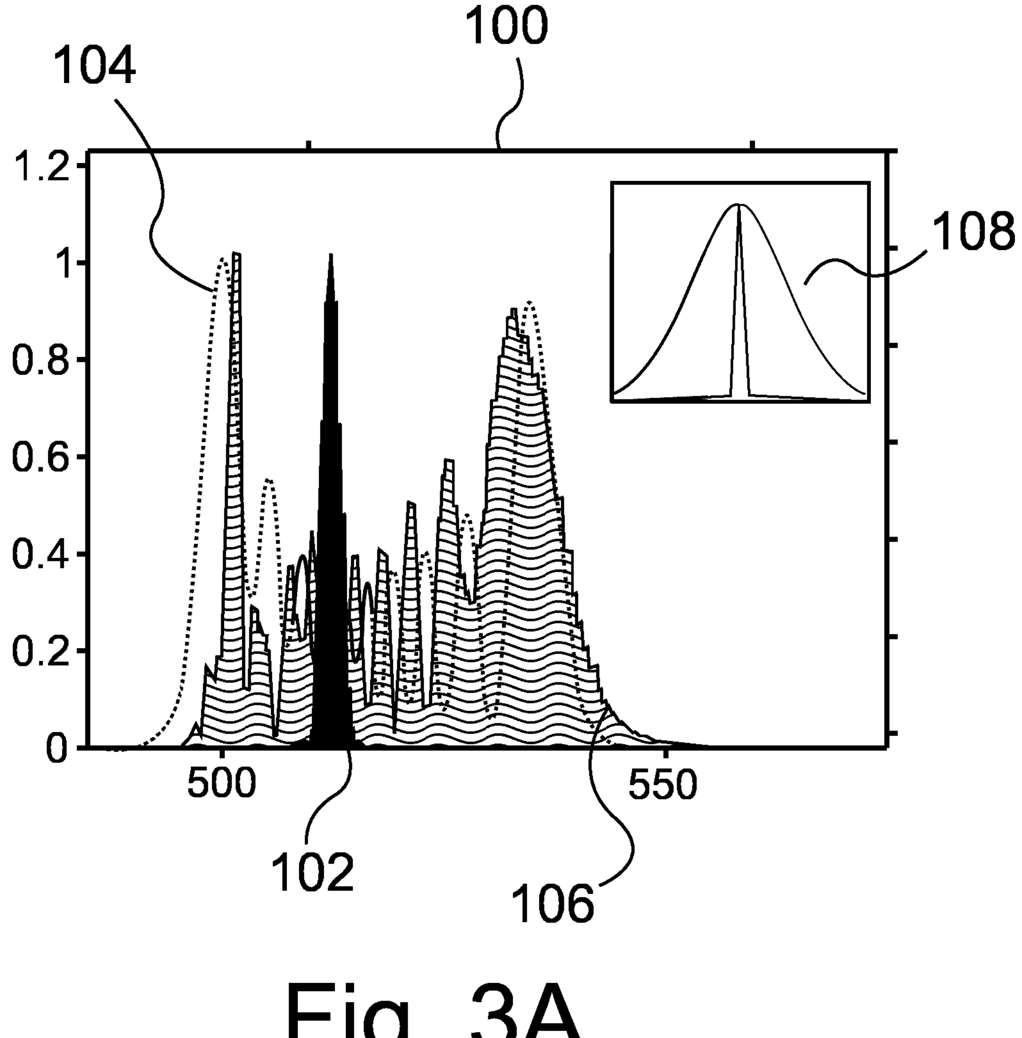
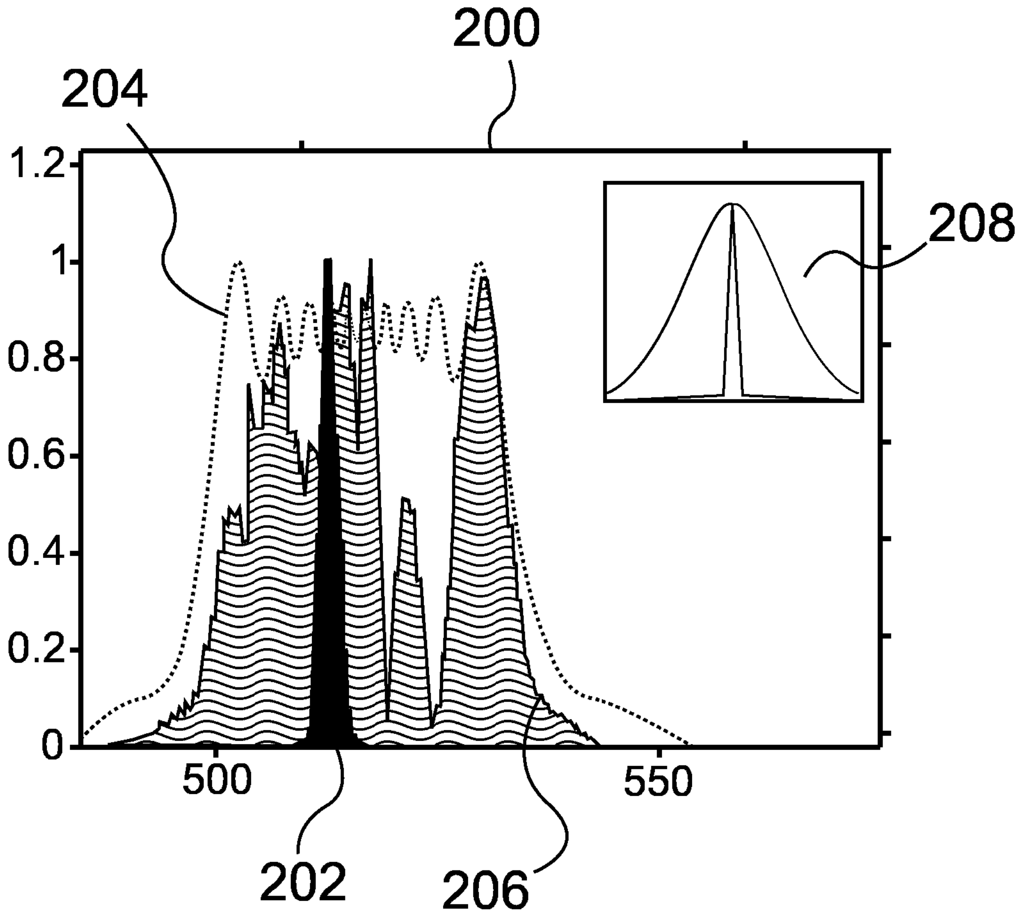


Fig. 3A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204
208
1.2
1
0.8
0.6
0.4
0.2
0
500
550
202
206

Fig. 3B

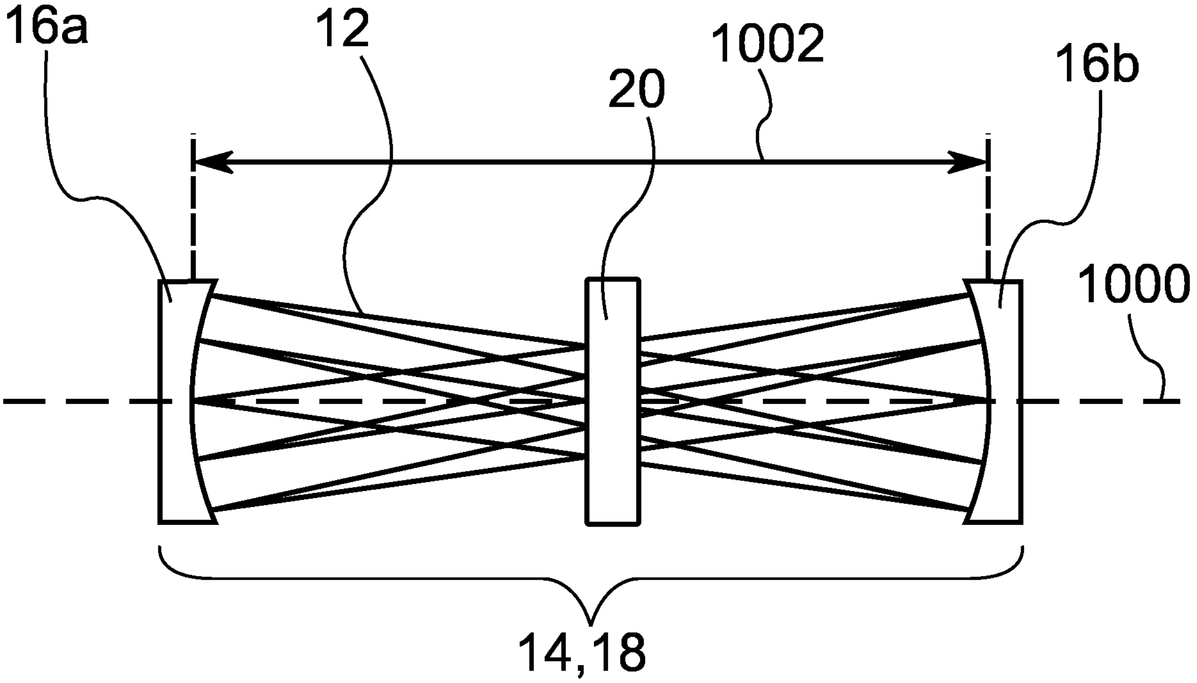
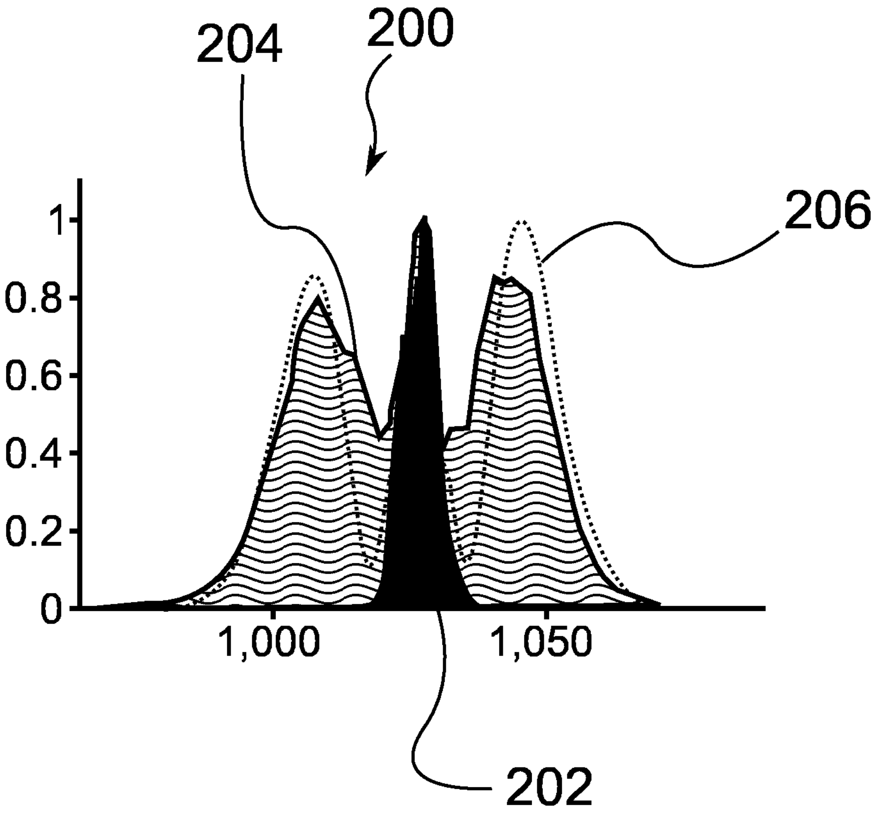

16a
12
1002
20
16b
1000
14,18

Fig. 4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206
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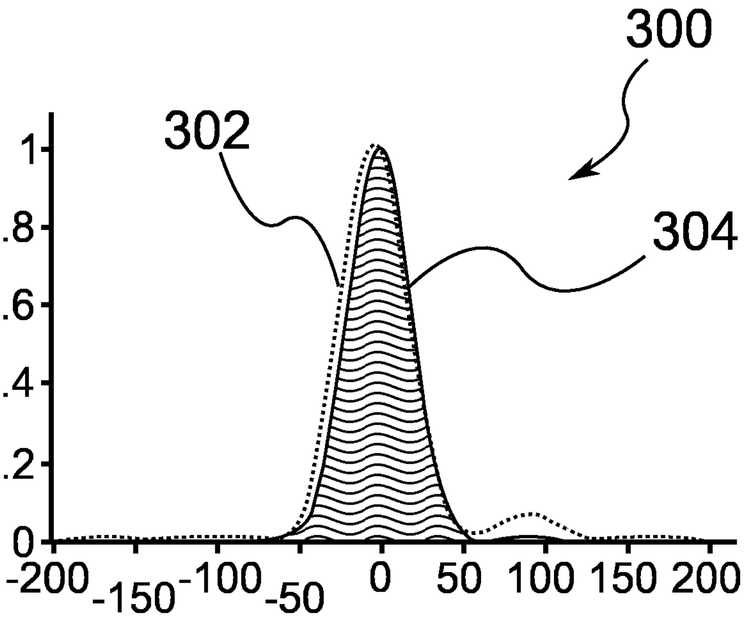
0.6
0.4
0.2
0
1,000
1,050

Fig. 5A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302
304
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0.6
0.4
0.2
0
-200
-150
-100
-50
0
50
100
150
200

Fig. 5B

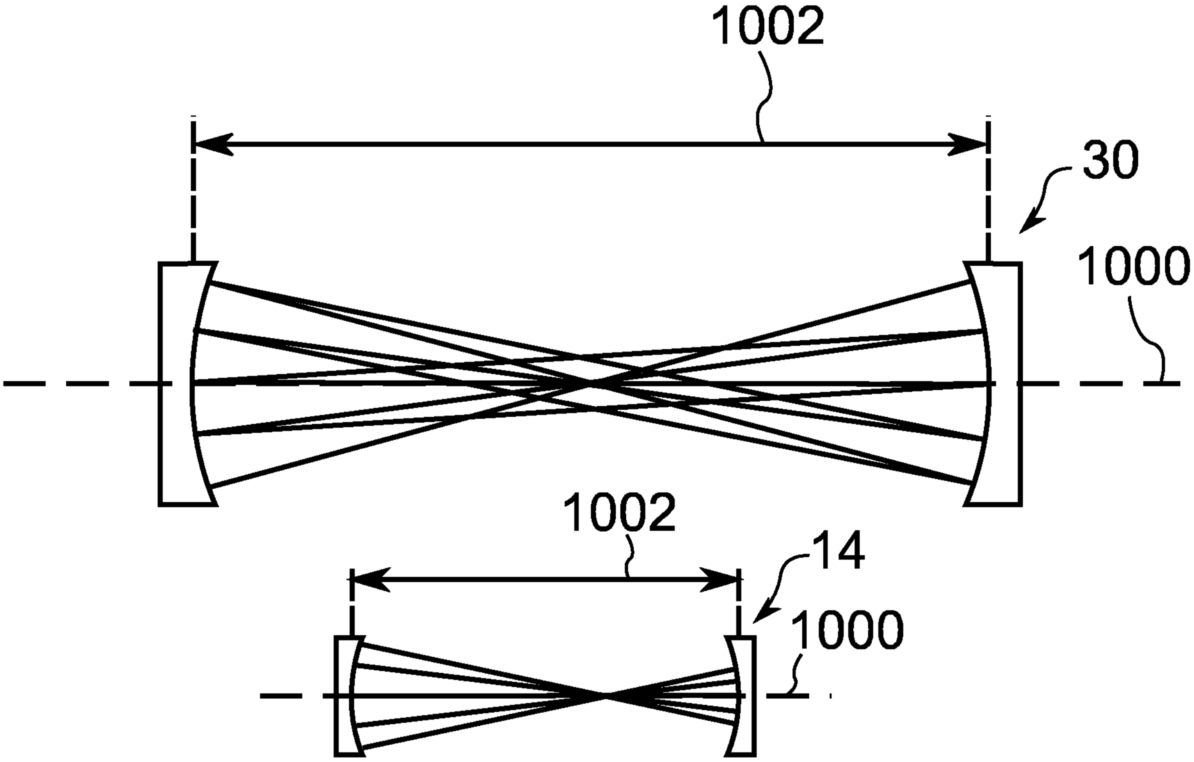

Fig. 6

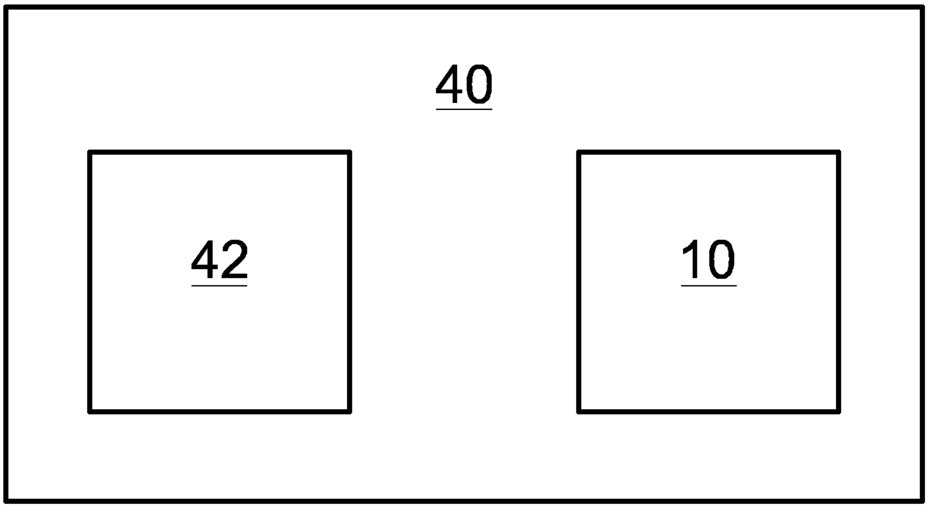

Fig. 7

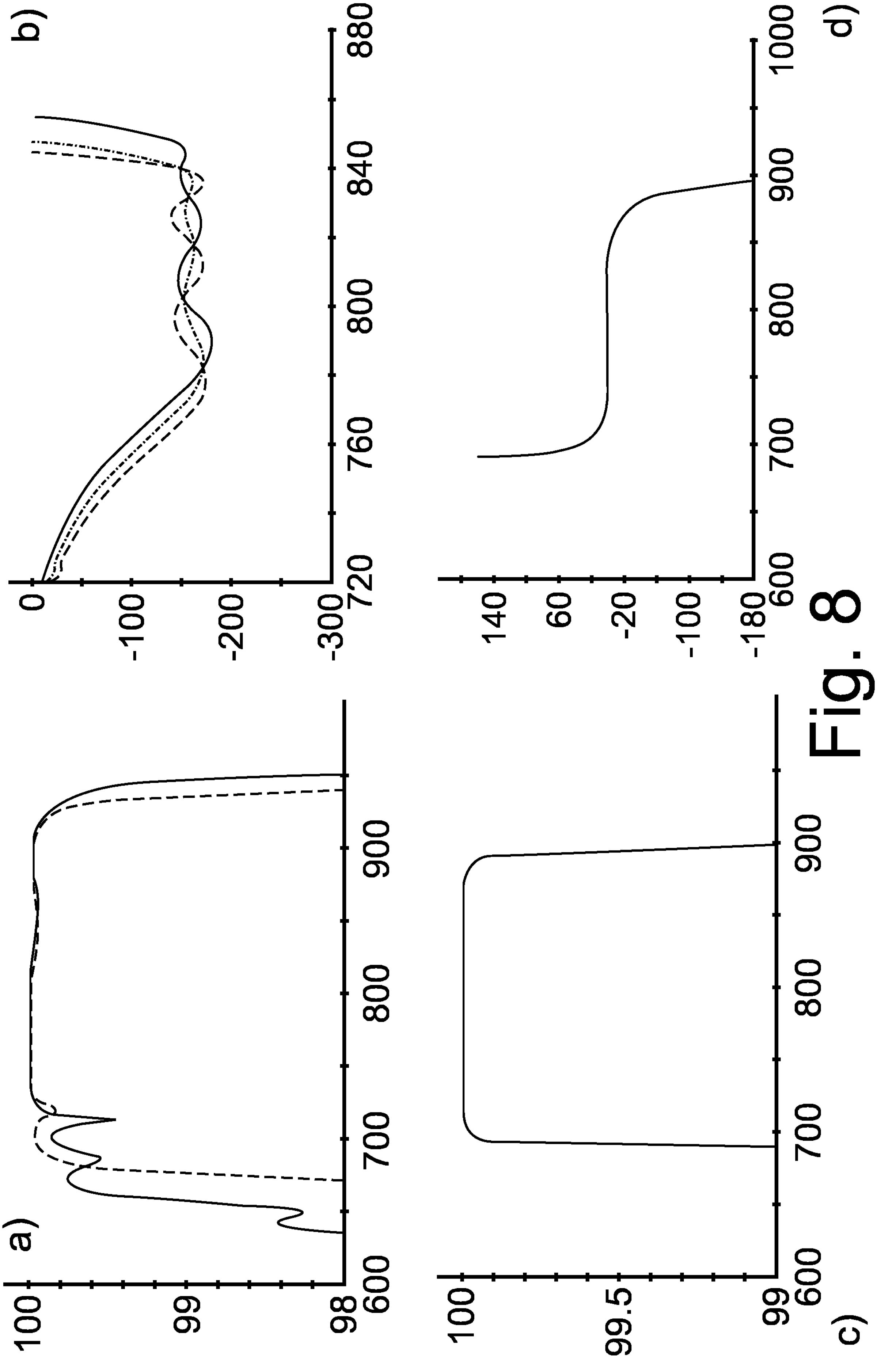
a)
100
99
98
600
700
800
900
b)
0
-100
-200
-300
720
760
800
840
880
c)
100
99.5
99
600
700
800
900
d)
140
60
-20
-100
-180
600
700
800
900
1000

Fig. 8

# INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2022/081025

**A. CLASSIFICATION OF SUBJECT MATTER**
INV. H01S3/05 H01S3/00 H01S3/08 G02B17/00 G02B17/06
G02F1/35 G02F1/01 G01J3/10
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
G01J H01S G02F G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | WO 2012/142549 A1 (ISOSPEC TECHNOLOGIES LP [US]; BORYSOW JACEK [US]; FINK MANFRED [US]) 18 October 2012 (2012-10-18)<br>paragraphs [0012], [0016]; figure 1<br>----- | 1,2,4,9,<br>19 |
| X | MONDELAIN ET AL: "Performance of a Herriott cell, designed for variable temperatures between 296 and 20K", JOURNAL OF MOLECULAR SPECTROSCOPY, ACADEMIC PRESS, US, vol. 241, no. 1, 12 January 2007 (2007-01-12), pages 18-25, XP005768435, ISSN: 0022-2852, DOI: 10.1016/J.JMS.2006.10.012<br>p. 20, right col. - p. 22, left col, first par.;<br>figure 1<br>----- | 1-5,7,8,<br>19 |

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

| | |
|---|---|
| Date of the actual completion of the international search<br>31 January 2023 | Date of mailing of the international search report<br>10/02/2023 |
| Name and mailing address of the ISA/<br>European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Authorized officer<br>Haan, Martine |

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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| X | HANNA MARC ET AL: "Nonlinear temporal compression in multipass cells: theory",<br>JOURNAL OF THE OPTICAL SOCIETY OF AMERICA - B.,<br>vol. 34, no. 7, 5 June 2017 (2017-06-05), page 1340, XP055802815,<br>US<br>ISSN: 0740-3224, DOI: 10.1364/JOSAB.34.001340<br>the whole document<br>----- | 1,6,<br>11-16,<br>18,19,<br>21,24-31 |
| X | CAO HUABAO ET AL: "Multipass-cell-based post-compression of radially and azimuthally polarized pulses to the sub-two-cycle regime",<br>JOURNAL OF THE OPTICAL SOCIETY OF AMERICA - B.,<br>vol. 36, no. 9,<br>19 August 2019 (2019-08-19), pages 2517-2525, XP055847378,<br>US<br>ISSN: 0740-3224, DOI: 10.1364/JOSAB.36.002517<br>figure 1; table 1<br>----- | 1,4-6,8,<br>11-14,<br>16-31 |
| X | JARGOT GAËTAN ET AL: "Self-compression in a multipass cell",<br>OPTICS LETTERS,<br>vol. 43, no. 22,<br>14 November 2018 (2018-11-14), page 5643, XP055878766,<br>US<br>ISSN: 0146-9592, DOI: 10.1364/OL.43.005643<br>p. 5644 last par. of the right column; figure 1<br>----- | 1,4,5,8,<br>11,12,<br>18,19,<br>24-31 |
| X | LAVENU LOIC ET AL: "High-Efficiency Nonlinear Compression Using a Gas-Filled Multipass Cell",<br>2019 CONFERENCE ON LASERS AND ELECTRO-OPTICS (CLEO), OSA,<br>5 May 2019 (2019-05-05), pages 1-2, XP033570702,<br>DOI: 10.23919/CLEO.2019.8750595<br>[retrieved on 2019-06-27]<br>figure 1<br>-----<br>-/-- | 1,11-19,<br>21,24-31 |

**C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | WAHID AMMAR BIN ET AL: "Supercontinuum Generation in a Nitrogen filled Multipass Cell",<br>2021 CONFERENCE ON LASERS AND ELECTRO-OPTICS EUROPE & EUROPEAN QUANTUM ELECTRONICS CONFERENCE (CLEO/EUROPE-EQEC), IEEE,<br>21 June 2021 (2021-06-21), page 1, XP033978385,<br>DOI: 10.1109/CLEO/EUROPE-EQEC52157.2021.9542058<br>[retrieved on 2021-09-20]<br>section 2 experimental setup and results; figure 1<br>----- | 1-31 |

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Information on patent family members

International application No
PCT/EP2022/081025

| Patent document cited in search report | | Publication date | Patent family member(s) | | | Publication date |
|---|---|---|---|---|---|---|
| WO 2012142549 | A1 | 18-10-2012 | NONE | | | |
| EP 3671184 | A1 | 24-06-2020 | CA | 3065699 | A1 | 21-06-2020 |
| | | | DE | 102018009981 | A1 | 25-06-2020 |
| | | | EP | 3671184 | A1 | 24-06-2020 |
| | | | US | 2020200676 | A1 | 25-06-2020 |